Weed Management in Nonirrigated Glyphosate-Resistant and Non-Resistant Soybean following Deep and Shallow Fall Tillage

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ABSTRACT

Management inputs that maximize economic return from the early plantings of soybean [*Glycine max* (L.) Merr.] in the midsouthern USA have not been evaluated fully. The objective was to compare perennial weed control in and yields and economic returns from plantings of maturity group (MG) IV and V soybean cultivars grown in the field under different weed management systems (WMS) following shallow (ST) and deep (DT) fall tillage. Adjacent experiments were conducted on Tunica clay (clayey over loamy, smectitic, nonacid, thermic Vertic Haplaquept) near Stoneville, MS (lat. 33°26′N). Weed management systems were (i) glyphosate [*N*-(phosphonomethyl)glycine]-resistant (GR) cultivars with preemergent (PRE) nonglyphosate herbicides followed by postemergent (POST) glyphosate; (ii) GR cultivars with POST glyphosate; (iii) non-GR cultivars with PRE plus POST nonglyphosate herbicides; and (iv) non-GR cultivars with POST nonglyphosate herbicides. Control of perennial redvine [*Brunnichia ovata* (Walt.) Shinners] declined in the ST environment when non-GR cultivars were used, but this did not result in a yield decline. Control of perennial johnsongrass [*Sorghum halepense* (L.) Pers.] at the end of the study period averaged <40% when non-GR cultivars were used and >93% when GR cultivars were used regardless of tillage treatment, and this was associated with lower yield. Use of PRE + POST vs. POST-only weed management sometimes resulted in lower profits regardless of fall tillage treatment. The fall tillage treatment × WMS interaction was not significant for yield or net return, which indicates that use of DT for perennial weed management is not economical.

The early soybean production system (ESPS) uses early maturing cultivars that are planted from late March through late April in the midsouthern USA. These cultivars begin blooming in May, start setting pods in late May to early June, and reach full seed (R6) in mid-July to early August. The reason for using this system and its requisite early maturing cultivars is to avoid drought that can adversely affect later-maturing, full-season cultivars that are normally planted in early May and later. Using the ESPS results in maximum yields in the midsouthern USA (Heatherly and Spurlock, 1999; Heatherly, 1999a). Tillage system can affect growth of soybean in ESPS plantings (Heatherly and Spurlock, 2001), and this in turn may affect weed populations in early maturing soybean cultivars. These tillage-related weed management possibilities may entail adopting different weed control strategies for different tillage management systems used for ESPS plantings. Effect of tillage in combination with varying weed management on weed populations in and yields from nonirrigated ESPS plantings has not been determined.

Redvine is a perennial, woody dicot vine that occurs extensively in crop and non-crop lands in the lower Mississippi River alluvial flood plain. Redvine is difficult to control because it can propagate from a deep and extensive root system (Elmore et al., 1989a, 1989b). Shallow tillage (≤15 cm) is often ineffective for its control because new flushes of shoots emerge from large, long woody rootstocks that are not affected by such tillage. In fact, Koskinen and McWhorter (1986) predicted increased populations of perennial and biennial weeds such as redvine from using reduced tillage systems. It is surmised that deep tillage (*subsoiling* usually >30 cm deep) in the fall can physically break up the network of rootstocks, and root segments that are brought to the surface will be destroyed by exposure to ambient conditions in the winter and early spring. Thus, deep tillage of clay soils can be considered for managing problem perennial weeds such as redvine.

Some herbicides [e.g., acifluorfen (sodium (5-[2-chloro-4-(trifluoromethyl)phenox]-2-nitrobenzoate), glufosinate (glufosinate–ammonimum), and paraquat (1,1′-dimethyl-4,4′-bipyridinium dichloride)] effectively remove top growth of perennial weeds, but have little effect on the rootstock. Destruction of foliage is temporary and partial, and new sprouts subsequently arise. Glyphosate, a nonselective systemic herbicide, has activity on redvine. In greenhouse studies, glyphosate at 3.36 kg a.e. (acid-equivalent) ha^{-1} controlled redvine 98% (Reddy, 2000). In field studies, however, control was <86% when two sequential applications of 840 g a.e. ha^{-1} were applied to GR soybean (Reddy and Chachalis, 2000). The label use rate specifically limits single (1.68 kg a.e. ha^{-1}) and sequential (840 g a.e. ha^{-1}) in-season applications to <2.52 kg a.e. ha^{-1} in GR soybean. Thus, effective control of redvine in transgenic soybean requires glyphosate applied at rates that are higher than those used for normal in-season weed control. The challenge, then, is to develop an economical strategy to manage redvine in soybean production systems that exploit the benefits of deep fall tillage and GR soybean cultivars.

Wesley and Smith (1991) performed deep tillage on a Tunica silty clay soil in the fall in Mississippi following soybean harvest when the soil profile was dry. They measured significant yield increases from soybean planted in May that was not irrigated in years when drought occurred during the growing season, and determined that

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Abbreviations: DT, deep tillage; ESPS, early soybean production system; GR, glyphosate-resistant; MG, maturity group; POST, postemergent; PRE, preemergent; ST, shallow tillage; WMS, weed management system.

net return was greatly increased from this practice (Wesley et al., 2000). The increased production was associated with increased moisture content in the soil, presumably because of greater infiltration and storage of winter rain resulting from deep tillage. This work has been used to promote deep tillage of dry clay soils in the fall in the midsouthern USA.

Studies on Sharkey clay (very-fine, smectitic, thermic Chromic Epiaquert) in Arkansas (Popp et al., 2001) and Mississippi (Wesley et al., 2001) showed average yield increases of 580 kg ha^{-1} and 365 kg ha^{-1}, respectively, and average increases in net return of \$96 and \$71 ha^{-1}, respectively, from fall deep tillage. In the Arkansas study, yields following fall deep tillage were significantly greater than those from conventional tillage even though drought was not severe. The Mississippi study used estimated deep tillage costs that were \$17 to \$20 ha^{-1} more than those for a treatment that received only shallow tillage ($\leq$10 cm). Heatherly and Spurlock (2001) and Heatherly et al. (2002a) determined that profits from producing soybean following deep tillage of Sharkey clay were significantly greater than those from conventional tillage only when plantings were made in April vs. May and later. In their study, costs associated with deep tillage were \$29 to \$42 ha^{-1} greater than those for a conventional shallow tillage system (fall tillage with a disk harrow and/or a spring-tooth harrow) because of expense associated with deep tillage and one extra shallow tillage operation to smooth the soil surface following deep tillage. In extremely dry years (yield levels $<$1000 kg ha^{-1}), deep tillage provided no yield or economic benefit (Heatherly et al., 2002a). On a Coastal Plain loamy sand soil in South Carolina, Frederick et al. (2001) measured a 12% yield increase from deep tillage just before May planting of soybean that was not irrigated compared to no deep tillage (2415 vs. 2160 kg ha^{-1}).

Weed management systems for soybean generally involve two basic approaches: use of preemergent followed by postemergent herbicides, and use of postemergent-only herbicides. Herbicides applied only postemergent can be used effectively to control early-season weeds (Reddy et al., 1999; Heatherly et al., 2002b, 2003a, 2003b) in midsouthern USA soybean plantings. Economically feasible weed control strategies using preemergent and postemergent herbicides in nonirrigated ESPS plantings following shallow and deep fall tillage have not been determined.

Clayey (silty clay loam, silty clay, clay) soils occupy more than 3.65 million ha or about 50% of the land area in the lower Mississippi River alluvial flood plain in the midsouthern USA. These clay soils crack when dried and swell when wetted, and have poor internal drainage when wet. Sharkey and Tunica are prominent clayey series, with the Tunica soils having coarser-textured materials starting at about 60 to 75 cm below the upper clay layers. Much of the area occupied by clayey soils in the region is cropped to soybean, and redvine and johnsongrass are prominent perennial weeds. The objective of this work was to assess perennial weed control in and compare yields and economic returns from April plantings of MG IV and MG V GR and non-GR soybean grown using two weed management systems without irrigation following shallow and deep tillage of clay soil in the fall. The reason for conducting this research was based on the premise that fall tillage and in-season weed management systems might act synergistically to effectively control perennial weeds and enhance soybean yield and economic return. Economic analysis of 3 yr of results was conducted to assess and compare the profitability of weed management systems in the two tillage environments.

MATERIALS AND METHODS

Nonirrigated field studies were conducted on Tunica clay soil in 2000, 2001, and 2002 near the Delta Research and Extension Center at Stoneville, MS (33°26′N). The site for the study was chosen because it was infested with redvine and johnsongrass in past years. Separate but adjacent experiments receiving either shallow fall tillage (ST) or deep fall tillage (DT) were established and maintained for the duration of the study period. Separate experiments were conducted to ensure that water drainage was not disrupted by the different soil surface environments that result from the different tillage treatments on this soil. In the fall of 1998, deep tillage was performed on the entire study area to ensure a uniform environment at the initiation of the experiment. In the spring of 1999, the experiment was established by assigning cultivars (main plot) and weed management systems (subplot) to experimental units where they remained for the duration of the research.

Experiments were conducted in a randomized complete block design with a split-plot factorial arrangement of treatments and four replicates within each tillage environment. In early October of 1999 and subsequent years, one-half of the area (same area each year) was deep-tilled (DT) with an implement having curved tines spaced 1 m apart, and one-half of the area (same area each year) was shallow-tilled (ST) using a disk harrow and/or spring-tooth cultivator. The deep tillage was done approximately 0.4 to 0.45 m deep. The shallow tillage was done approximately 10 cm deep. Rainfall during the 30 d preceding deep tillage was 29 mm in 1999, 66 mm in 2000, and 21 mm in 2001; thus, soil was relatively dry preceding each year's deep tillage. Shallow tillage (two passes on ST and three on DT) with a disk harrow and/or a spring-tooth cultivator was conducted after completion of deep tillage each year. Weather data in Table 1 were collected about 4 km from the experimental site.

Seed of MG IV GR ('SG 498') and MG V GR ('A 5701') and MG IV non-GR ('AP 4882') and MG V non-GR ('P 9594') cultivars were planted on 20 Apr. 2000, 29 Mar. 2001, and 15 Apr. 2002. Cultivars were chosen because of their consistent high performance on a large hectarage in the region. A plate planter was used that contained double-disk openers and closing wheels to seal the seed trench. Seed were treated before planting with mefenoxam [(R)-2-{2,6-(dimethylphenyl)-methoxyacetylamino}-propionic acid methyl ester] fungicide as a precaution against *Pythium* spp. Row spacing was 0.5 m and seeding rate was 15 to 18 seed m^{-1} of row, which resulted in 295 000 to 345 000 planted seed ha^{-1}. Plots were 25 m long and 8.1 m (16 rows) wide. Plantings were made into a stale seedbed (untilled following fall tillage and before planting in the spring; Heatherly, 1999b) following application of glyphosate at 840 g a.e. ha^{-1} to kill weed vegetation.

Weed management systems were selected along the following premises. First, uncontrolled weeds will reduce soybean yield; therefore, no weedy check was included. The intent in this experiment was to ensure that both weed management

Table 1. Average daily maximum air temperatures (Max. T) and total rainfall amounts (Rain) for indicated months; dates of beginning pod (R3) and full seed (R6) stages of maturity group (MG) IV and MG V soybean cultivars planted on the same dates within 2000, 2001, and 2002, respectively; and 30-yr temperature and rainfall averages at Stoneville, MS.

	2000				2001				2002				1964–1993 averages†	
Month	Max. T	Rain	R3	R6	Max. T	Rain	R3	R6	Max. T	Rain	R3	R6	Max. T	Rain
	°C	mm	— date, MG‡ —		°C	mm	— date, MG‡ —		°C	mm	—— date, MG‡ ——		°C	mm
April	22.2	282			25.6	101			24.4	83			23.5	137
May	29.5	176			30.0	129	25, IV		28.3	72			28.0	127
June	32.2	156	23, IV		31.1	70	18, V		31.7	105	14, IV		32.0	94
July	34.4	16	5, V		33.3	80		23, IV	33.8	84	3, V		33.0	94
August	36.7	0		11, IV	32.8	215		25, V	33.9	70		5, IV; 26, V	32.5	58
September	31.1	66		1, V	29.4	77			31.7	196			29.5	86

† Boykin et al., 1995.
‡ Number is day of indicated month that the stage occurred, and IV or V is MG in which indicated stage occurred on that date.

systems controlled weeds until canopy closure. Second, the inclusion of economic analyses in this study dictated that both weed management systems be practical and realistic. Also, there was no intent to determine how weed management systems related to an economically unattainable or unfeasible weed-free environment. Therefore, a weed-free check was not included. Finally, the intent was to assess the effect of using the two accepted approaches for weed management in soybean, which are a system with a preemergent component and a system that relies solely on postemergent-only control. Based on these premises, the eight weed management systems were: (i) MG IV GR cultivar with weed control using PRE nonglyphosate herbicides followed by POST applications of glyphosate; (ii) MG V GR cultivar with weed control using PRE nonglyphosate herbicides followed by POST applications of glyphosate; (iii) MG IV GR cultivar with weed control using POST applications of glyphosate; (iv) MG V GR cultivar with weed control using POST applications of glyphosate; (v) MG IV non-GR cultivar with weed control using PRE plus POST nonglyphosate herbicides; (vi) MG V non-GR cultivar with weed control using PRE plus POST nonglyphosate herbicides; (vii) MG IV non-GR cultivar with POST weed control using nonglyphosate herbicides; and (viii) MG V non-GR cultivar with POST weed control using nonglyphosate herbicides. Herbicides applied to each weed management system across ST and DT were the same and were applied at the same time in ST and DT within each year.

Within each weed management system for GR and non-GR cultivars, use of herbicides and their combinations was dictated by expected weed populations (PRE + POST) or actual populations (POST). Selection of postemergent herbicides for the non-GR cultivars was based on weekly assessment of the presence and size of particular weed species in plots of each weed management system. The objective was to minimize weed competition within the constraints of each individual weed management system. Preemergent herbicides were applied immediately after planting each year. In each year, rainfall of at least 13 mm occurred within 10 d of preemergent application. Preemergent herbicides and postemergent broadleaf herbicides were applied in 187 L ha^{-1} water, whereas postemergent grass herbicides and glyphosate were applied in 94 L ha^{-1} water. Herbicides were applied using a canopied sprayer (Ginn et al., 1998a) for over-the-top applications (to prevent drift to adjacent plots of different systems) or a directed sprayer (Ginn et al., 1998b) for applications underneath the developing soybean canopy.

Herbicides (Table 2) were broadcast-applied each year at labeled rates with recommended adjuvants and in recommended tank mixes. Rates for preemergent herbicides applied to both GR and non-GR cultivars were a premix of metribuzin {4-amino-6-(1,1-dimethylethyl)-3-(methylthio)-1,2,4-triazin-5(4*H*)-one} at 450 g a.i. ha^{-1} plus chlorimuron ethyl [ethyl 2-{{{{(4-chloro-6-methoxypyrimidin-2-yl)amino}carbonyl}amino}sulfonyl}benzoate] at 75 g a.i. ha^{-1} applied in 2000 and 2001, and imazaquin {2-[4,5-dihydro-4-methyl-(1-methylethyl)-5-oxo-1*H*-imidazol-2-yl]-3-quinolinecarboxylic acid} at 137 g a.i. ha^{-1} applied in 2002. Rates for postemergent herbicides applied to non-GR cultivars were: premix of 560 g a.i. ha^{-1} bentazon [3-(isopropyl)-1*H*-2,1,3-benzothiadiazin-4-(3*H*)-one 2,2-dioxide] and 280 g a.i. ha^{-1} acifluorfen [sodium [5-{2-chloro-4-(trifluoromethyl)-phenoxy}-2-nitrobenzoate]; premix of 560 g a.i. ha^{-1} bentazon plus 280 g a.i. ha^{-1} acifluorfen plus 140 g a.i. ha^{-1} clethodim [(*E*)-

Table 2. Preemergent (PRE) and postemergent (POST) herbicides applied to weed management systems (WMS) for nonirrigated glyphosate-resistant (GR) and non-GR soybean grown at Stoneville, MS, 2000–2002.

WMS	Herbicide†‡
	2000
GR PRE + POST	PRE metribuzin + chlorimuron; POST glyphosate (2×)
GR POST	Glyphosate (3×)
Non-GR PRE + POST	PRE metribuzin + chlorimuron; POST sethoxydim fb bentazon + acifluorfen + clethodim fb bentazon + acifluorfen
Non-GR POST	Bentazon + acifluorfen + clethodim (2×) fb bentazon + acifluorfen
	2001
GR PRE + POST	PRE metribuzin + chlorimuron; POST glyphosate
GR POST	Glyphosate (2×)
Non-GR PRE + POST	PRE metribuzin + chlorimuron; POST sethoxydim fb bentazon + acifluorfen + clethodim
Non-GR POST	Bentazon + acifluorfen + clethodim fb fomesafen
	2002
GR PRE + POST	PRE imazaquin; POST glyphosate (2×)
GR POST	POST glyphosate (2×)
Non-GR PRE + POST	PRE imazaquin; POST bentazon + acifluorfen fb sethoxydim fb fluazifop fb 2,4-DB + metribuzin
Non-GR POST	Bentazon + acifluorfen fb sethoxydim fb fluazifop fb 2,4-DB + metribuzin

† + Indicates either a premix or a tankmix; 2× or 3× indicates two or three applications, respectively; fb = followed by.
‡ Rates of herbicides, g a.i. (a.e. for glyphosate) ha^{-1}: metribuzin, 450, + chlorimuron, 75; imazaquin, 137; glyphosate, 840; sethoxydim, 213; bentazon, 560, + acifluorfen, 280, + clethodim, 140; fomesafen, 213; fluazifop, 213; 2,4-DB, 224, + metribuzin, 280.

2{1-{{(3-chloro-2-propenyl)oxy}imino}propyl}-5-{2-(ethylthio) propyl}-3-hydroxy-2-cyclohexen-1-one]; fomesafen {5-[2-chloro-4-(trifluormethyl)phenoxy]-*N*-(methylsulfonyl)-2-nitrobenazmide} at 213 g a.i. ha^{-1}; fluazifop {(*R*)-2-[4-[[5-(trifluoromethyl)-2-pyridinyl]oxy]phenoxy]propanoate} at 213 g a.i. ha^{-1}; sethoxydim [2-{1-(ethoxyimino)butyl}-5-{2-(ethylthio)propyl}-3-hydroxy-2-cyclohexen-1-one] at 213 g a.i. ha^{-1}; clethodim [(*E*)-2{1-{{(3-chloro-2-propenyl)oxy}imino}propyl}-5-{2-(ethylthio)propyl}-3-hydroxy-2-cyclohexen-1-one] at 105 g a.i. ha^{-1}; and a tankmix of 2,4-DB {4-(2,4-dichlorophenoxy)butyric acid, dimethylamine salt} at 224 g a.i. ha^{-1} plus metribuzin at 280 g a.i. ha^{-1} applied as a directed spray underneath the soybean canopy.

Single and/or sequential applications of glyphosate at 840 g a.e. ha^{-1} were made postemergent to GR cultivars (Table 2). This is less than the maximum allowable rate of 1.68 kg a.e. ha^{-1} for a single application, and in all but one case (GR POST in 2000; Table 2), less than the total allowable in-season rate of 2.52 kg a.e. ha^{-1}. Thus, an increase to the allowed maximum for individual and/or total in-season applications of glyphosate may have changed the results of this study. However, the intent of this study was to use a standard rate (840 g a.e. ha^{-1}) of glyphosate in conjunction with fall deep tillage to determine if the two acted synergistically to control redvine.

The degree of weed control was assessed after soybean leaf senescence each year to measure the season-long effect of weed management systems that were intended to provide complete weed control. Control of individual weed species was visually estimated based on weed cover in each plot on a scale of 0 (no weed control) to 100% (complete weed control). Because the extent of weed cover present in plots was related to the effect of each weed management system, the weed cover estimates were used to compare the varying weed management systems. This is similar to the method used by Heatherly et al. (2003b) to estimate weed control in GR and non-GR soybean systems at the end of the growing season. Weed control data were subjected to analysis of variance using PROC MIXED (SAS Inst., 1998) to determine significance of main effects and any interactions among main effects. Means were separated at the 0.05 level of probability using Fisher's Protected LSD test. Estimates of weed cover in 1999 were used to determine initial redvine population levels.

A field combine modified for small plots was used to harvest the four center rows in plots on 11 and 21 Sept. 2000, 14 Sept. and 4 Oct. 2001, and 7 Sept. and 2 Oct. 2002. Seed from all plots were cleaned by the harvesting machine. Thus, correction for foreign matter content in seed was not necessary in any year. Harvested seed were weighed, moisture content was determined, and weights were adjusted to 130 g moisture kg^{-1} seed. Yield data from 1999 are not used in the yield analysis since the entire site had been deep-tilled preceding the 1999 growing season.

Estimates of total expenses (excluding charges for land, management, and general farm overhead) and returns were developed for each annual cycle of each experimental unit using the Mississippi State Budget Generator (Spurlock and Laughlin, 1992). Total specified expenses were calculated using actual inputs in each year of the experiment and included all operating expenses and machinery ownership costs, but excluded charges for land, management, and general farm overhead which were assumed to be the same for all treatment combinations. Machinery ownership costs for tractors, self-propelled harvesters, implements, and sprayers were estimated by computing the annual capital recovery charge for each machine and applying its per-hectare rate to each field operation. Operating expenses included those for: herbicides, adjuvants, seed, and labor; fuel, repair, and maintenance of machinery; hauling harvested seed; and interest on operating capital. Weed management expenses after planting were calculated for each system, and included charges for herbicides, surfactants, and application, and the extra cost for seed of GR cultivars (Table 3). All application charges included both operating expenses and ownership costs associated with tractors and sprayers. Costs for machinery and operating expenses were based on prices paid by Mississippi farmers each year.

Table 3. After-planting weed management expense and total expense (excluding charges for land, management, and general farm overhead) for weed management systems (WMS) using preemergent (PRE) and postemergent (POST) herbicides applied to nonirrigated glyphosate-resistant (GR) and non-GR soybean grown following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, 2000–2002.

WMS	Weed expense‡	Total expense† DT	Total expense† ST
	$ ha^{-1}		
	2000		
GR PRE + POST	123	371–366	314–313
GR POST	94	339–335	283–282
Non-GR PRE + POST	185	441–430	383–378
Non-GR POST	158	410–402	354–347
	2001		
GR PRE + POST	97	325–347	282–294
GR POST	65	305–310	250–261
Non-GR PRE + POST	147	386–397	331–345
Non-GR POST	82	319–329	265–278
	2002		
GR PRE + POST	102	370–372	318–322
GR POST	65	329–330	279–279
Non-GR PRE + POST	175	440–440	404–393
Non-GR POST	138	398–396	350–351
	2001–2002 avg.		
GR PRE + POST	107	355–362	305–310
GR POST	75	324–325	270–274
Non-GR PRE + POST	169	422–422	372–372
Non-GR POST	126	376–375	323–325

† First number in each column for MG IV cultivar; second number for MG V cultivar. Difference attributable to different planting seed costs and different hauling expenses associated with different yields.
‡ Includes extra seed cost for GR cultivars of \$21 ha^{-1} in 2000 and 2001 and \$22 ha^{-1} in 2002.

The 2000 and 2001 USDA loan rate of \$0.196 kg^{-1} seed for Mississippi was used to calculate income from each experimental unit each year. Net return above total specified expenses was determined for each experimental unit each year. Analysis of variance [PROC MIXED (SAS Inst., 1996)] was used to evaluate the significance of treatment effects on seed yield and net return. Analyses across years treated year as a fixed effect to determine interactions involving year. Analyses for individual years treated cultivar and weed management system as fixed effects. Mean separation was achieved with an $LSD_{0.05}$.

RESULTS AND DISCUSSION

Weather

Average daily maximum air temperature and total rainfall for growing season months in 2000, 2001, and 2002, and 30-yr temperature and rainfall averages for Stoneville, MS (Boykin et al., 1995) are presented in Table 1. In all years of the study, average monthly maximum air temperatures generally were near the 30-yr average from April through June (Table 1). April through June rain was greatly above the 30-yr average in 2000, slightly below average in 2001, and greatly below average in 2002. The MG IV cultivars reached beginning pod (R3) on 23 June 2000, 25 May 2001, and 14 June 2002, while MG V cultivars reached R3 on 5 July 2000, 18 June 2001, and 3 July 2002 (Table 1). Thus, the vegetative through early reproductive period of all cultivars generally was subjected to greater-than-average rainfall in 2000 and below-average rainfall in 2001 and 2002. The MG IV cultivars were at full seed (R6) on 11 Aug. 2000, 23 July 2001, and 5 Aug. 2002, whereas MG V cultivars were at R6 on 1 Sept. 2000, 25 Aug. 2001, and 26 Aug. 2002 (Table 1). In 2000, July and August average monthly maximum air temperatures were above average and rainfall was greatly below average. This resulted in extreme water-deficit stress during the R3 to R6 period, especially for MG V cultivars. In 2001 and 2002, July and August maximum air temperatures were near average. July 2001 rainfall was near average, while August 2001 rainfall was greatly above average. This above-average August rainfall in 2001 was especially timely for seed yield manifestation in the MG V cultivars. Rainfall in July and August of 2002 was near average and rain events were timely. Thus, weather conditions for manifestation of seed yield were better in 2001 and 2002 than in 2000.

Weed Management Expense and Total Expense

Cost of weed management for GR and non-GR cultivars was always less with POST-only than with PRE + POST application of herbicides (Table 3). The 3-yr average weed management cost for GR (includes extra seed cost shown in Table 3) and non-GR cultivars using POST was \$75 and \$126 ha^{-1}, and for PRE + POST was \$107 and \$169 ha^{-1}, respectively. Thus, weed management expense for non-GR cultivars was greater, even with a higher cost for seed of GR cultivars. Differences in total expenses (excluding charges for land, management, and general farm overhead) among WMSs followed the same pattern as the differences in weed management expenses (Table 3). Estimated expenses for DT averaged \$324 to \$422 ha^{-1}, while those for ST averaged \$270 to \$372 ha^{-1}.

Weed Control

In 1999 (first year following fall tillage), the fall tillage × WMS interaction was not significant for redvine control (Table 4). Redvine control averaged across fall tillage treatment ranged from 73 to 89%. In 2000 and 2001, the fall tillage × WMS interaction was not significant for redvine control at soybean maturity (Table 4). Thus, average redvine control values across fall tillage treatment are discussed for those 2 yr. In 2000, WMS did not significantly affect redvine control, which ranged from 75 to 92%. In 2001, redvine control in the MG V GR cultivar with PRE + POST weed management was greater than that in MG IV non-GR cultivars and the MG V non-GR cultivar with POST-only weed management. In 2002, the fall tillage × WMS interaction was significant. In the ST treatment, WMSs that had GR cultivars and glyphosate weed management resulted in greater control than did the MG IV non-GR cultivar or the MG V non-GR cultivar with POST-only weed management. The more complete canopy of the MG V non-GR cultivar that resulted from its longer growing season (Table 1), in combination with PRE + POST weed management, was effective in suppressing redvine in the ST environment. In the DT treatment, all WMSs had statistically similar redvine control.

The finding in 2001 indicates that GR cultivars and glyphosate herbicide are more effective in controlling redvine regardless of fall tillage treatment. The finding in 2002 (last year of study) indicates this is especially true when shallow fall tillage is used. Greater translocation of glyphosate than of nonglyphosate herbicides could have reduced regrowth of redvine (Reddy, 2000), which may be important with shallow fall tillage. When DT was used, both GR and non-GR cultivars with their accompanying herbicides were equally effective in controlling redvine. This may be attributable to taller plants in the DT treatment (Heatherly and Spurlock, 2001), which would have been important for the non-GR cultivars. Elmore et al. (1989a, 1989b) found that a fuller soybean canopy resulted in less perennial vine ground cover when non-GR cultivars were used.

In addition to redvine, johnsongrass and pitted morningglory (*Ipomoea lacunosa* L.) became dominant weed

Table 4. Redvine control at harvest in nonirrigated glyphosate-resistant (GR) and non-GR soybean grown under weed management systems (WMS) using preemergent (PRE) and postemergent (POST) applications of herbicides in plantings following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, 2000–2002.

	1999			2000			2001			2002	
WMS†	ST	DT	Avg.‡	ST	DT	Avg.‡	ST	DT	Avg.‡	ST	DT
	%										
MG IV GR PRE + POST	93	86	89 a	93	88	90 a	88	88	88 ab	90 a	85 a
MG V GR PRE + POST	90	85	88 ab	90	95	92 a	93	95	94 a	90 a	100 a
MG IV GR POST	88	90	89 a	85	88	86 a	83	90	86 ab	83 a	90 a
MG V GR POST	90	83	86 ab	93	85	89 a	75	90	82 ab	85 a	90 a
MG IV non-GR PRE + POST	73	74	73 c	73	85	79 a	53	75	64 c	55 c	90 a
MG V non-GR PRE + POST	93	83	88 ab	85	88	86 a	85	85	85 ab	78 a	88 a
MG IV non-GR POST	89	90	89 a	80	90	85 a	65	78	72 bc	53 c	88 a
MG V non-GR POST	73	80	76 bc	70	80	75 a	65	83	74 bc	55 c	90 a

† See Table 2 for herbicides and their rates.

‡ Average values in each column are (ST + DT)/2, and are based on four replicates in both ST and DT. Values within each column and year that are followed by the same letter are not significantly different at $p \leq 0.05$. The fall tillage × WMS interaction was significant only in 2002; however, ST and DT values are given for other years to show magnitude of values for each fall tillage treatment.

species by 2002. In 2002, johnsongrass control was not significantly affected by the fall tillage treatment × WMS interaction. Average control of johnsongrass following 4 yr of the same WMSs applied to the same plots was statistically equal between PRE + POST and POST when GR cultivars and glyphosate were used (Table 5). Control was significantly less in non-GR cultivars compared with GR cultivars across fall tillage treatment. When non-GR cultivars were used, PRE + POST weed management controlled johnsongrass better than POST-only weed management; however, control was low in all WMSs with non-GR cultivars. This population shift over the years may have been due to lack of control of rhizome johnsongrass and inadequate control of seedling johnsongrass with PRE herbicides as well as failure to control late-emerging flushes with POST nonglyphosate herbicides in non-GR cultivars. Failure to control johnsongrass with POST herbicides in non-GR weed management systems could have been due to antagonism associated with tank mixtures of grass (clethodim) and broadleaf (acifluorfen, bentazon) herbicides. Vidrine et al. (1995) demonstrated that broadleaf herbicides applied in mixtures were antagonistic toward the activity of grass herbicides. However, the premix of bentazon + acifluorfen + clethodim used in 2000 and 2001 (Table 2) was a recommended product by the Mississippi State University Extension Service, and the estimated level of johnsongrass control by this product was rated 9 out of 10. Therefore, its use was expected to provide johnsongrass control. In 2002, sethoxydim and fluazifop were applied following application of the bentazon + acifluorfen premix (Table 2) to avoid the possibility that an antagonism between the broadleaf and grass herbicides in the premix would contribute to poor johnsongrass control.

In 2002, pitted morningglory control was different among WMSs across both fall tillage treatments (Table 5). Control of pitted morningglory in the MG IV GR cultivar with POST-only glyphosate provided the lowest (84%) control, presumably because of the reduced efficacy of glyphosate and less canopy development for MG IV compared with MG V cultivars. The MG IV non-GR cultivar with POST-only weed management resulted in 92% control, which was statistically equal to the 90% control with the MG IV GR cultivar with PRE + POST weed management.

Table 5. Johnsongrass and pitted morningglory control at harvest in nonirrigated glyphosate-resistant (GR) and non-GR soybean grown under weed management systems (WMS) using preemergent (PRE) and postemergent (POST) applications of herbicides in plantings following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, 2002 (follows 3 yr of treatment imposition).

	Johnsongrass			Pitted morningglory		
WMS†	ST	DT	Avg.‡	ST	DT	Avg.‡
	%					
MG IV GR PRE + POST	93	100	96 a‡	88	93	90 b
MG V GR PRE + POST	100	98	99 a	100	100	100 a
MG IV GR POST	98	98	98 a	80	88	84 c
MG V GR POST	100	100	100 a	100	100	100 a
MG IV non-GR PRE + POST	35	40	38 b	98	100	99 a
MG V non-GR PRE + POST	40	18	29 bc	100	100	100 a
MG IV non-GR POST	15	18	16 cd	90	93	92 b
MG V non-GR POST	18	0	9 d	100	100	100 a

† See Table 2 for herbicides and their rates.
‡ Average values in each column are (ST + DT)/2, and are based on four replicates in both ST and DT. Values within each column that are followed by the same letter are not significantly different at $p \leq 0.05$. The fall tillage × WMS interaction was not significant for either weed, but ST and DT values are given to show magnitude of values for each fall tillage treatment.

Seed Yield and Net Return

Across-years analyses revealed significant interactions between tillage treatment and year and between WMS and year for both seed yield and net return. Also, weather patterns mentioned earlier and shown in Table 1 were different among the 3 yr. Therefore, individual-year results are discussed and related to data shown in Table 6.

2000

The fall tillage × WMS interaction was not significant for either seed yield or net return. Weed management system significantly affected both variables (Table 6). The four WMSs that included MG IV cultivars yielded the most and resulted in the greatest net returns. Using GR or non-GR cultivars and PRE + POST or POST-only weed control made no significant difference in either the ST or DT fall tillage treatment. All yields were relatively low, and only the MG IV cultivars produced yields that resulted in positive net returns. Evidently, the factor most affecting results in 2000 was the hot and dry July and August (Table 1), and the effect was greater for the late-maturing MG V cultivars. The lack of a significant fall tillage × WMS interaction indicates that tillage environment had no significant effect on results in this extremely dry year.

2001

As in 2000, the fall tillage × WMS interaction was not significant for either seed yield or net return. Weed management system significantly affected both variables (Table 6). The four WMSs that included MG V cultivars yielded the most and resulted in the greatest net returns. This apparently resulted from the above-normal rain in August (Table 1) that provided more water during seed fill of the MG V cultivars. Using GR or non-GR cultivars and PRE + POST or POST-only weed control made no significant difference when MG V cultivars were used. Glyphosate-resistant MG IV cultivars produced greater net returns than did non-GR MG IV cultivars. Using PRE + POST vs. POST-only weed control resulted in greater net returns when non-GR MG IV cultivars were used. As in 2000, the lack of a significant fall tillage × WMS interaction indicates that tillage environment had no significant effect on results.

2002

As in the previous 2 yr, the fall tillage × WMS interaction was not significant for either seed yield or net return. Weed management system significantly affected both variables (Table 6). Unlike the previous 2 yr, however, there was no advantage in yield or net return for

Table 6. Seed yield and net return from nonirrigated glyphosate-resistant (GR) and non-GR soybean grown under weed management systems (WMS) using preemergent (PRE) and postemergent (POST) applications of herbicides in plantings following shallow (ST) and deep (DT) fall tillage at Stoneville, MS, 2000–2002.

WMS†	Seed yield ST	Seed yield DT	Seed yield Avg.‡	Net return ST	Net return DT	Net return Avg.‡
	kg ha^{-1}			\$ ha^{-1}		
2000						
MG IV GR PRE + POST	1433	2241	1837 ab‡	−33	70	19 ab
MG V GR PRE + POST	1147	1494	1321 cd	−87	−72	−80 c
MG IV GR POST	1396	2159	1777 abc	−9	85	38 a
MG V GR POST	1123	1411	1267 d	−61	−58	−59 bc
MG IV non-GR PRE + POST	1608	2720	2164 a	−67	94	13 ab
MG V non-GR PRE + POST	1368	1432	1400 bcd	−109	−148	−129 c
MG IV non-GR POST	1675	2469	2072 a	−24	75	25 ab
MG V non-GR POST	1086	1570	1328 cd	−134	−93	−113 c
2001						
MG IV GR PRE + POST	1915	2450	2182 bc	94	156	125 b
MG V GR PRE + POST	3303	3557	3430 a	355	352	353 a
MG IV GR POST	2119	2590	2354 b	166	204	185 b
MG V GR POST	3310	3163	3236 a	390	312	351 a
MG IV non-GR PRE + POST	1597	2134	1865 c	−17	33	8 d
MG V non-GR PRE + POST	3304	3349	3327 a	304	262	283 a
MG IV non-GR POST	1637	2094	1865 c	57	92	74 c
MG V non-GR POST	3193	3173	3183 a	350	294	322 a
2002						
MG IV GR PRE + POST	3211	3517	3364 abc	313	321	317 bc
MG V GR PRE + POST	3684	3709	3696 a	402	357	380 ab
MG IV GR POST	3600	3522	3561 ab	428	364	396 a
MG V GR POST	3495	3650	3572 ab	408	387	397 a
MG IV non-GR PRE + POST	3482	2930	3206 abcd	280	136	208 d
MG V non-GR PRE + POST	3266	2786	3026 cd	249	108	178 d
MG IV non-GR POST	3288	2904	3096 bcd	296	173	234 cd
MG V non-GR POST	3155	2360	2758 d	269	68	169 d

† See Table 2 for herbicides and their rates.
‡ Average values in each column are (ST + DT)/2, and are based on four replicates in both ST and DT. Values within each column and year that are followed by the same letter are not significantly different at $p \leq 0.05$. The fall tillage × WMS interaction was not significant for either seed yield or net return in any year, but ST and DT values are given to show magnitude of values for each fall tillage treatment.

either MG IV or MG V cultivars. When MG IV cultivars were used, glyphosate resistance had no significant effect on yield, but resulted in greater net returns because of the lower cost of weed control for the GR cultivar (Table 3). When MG V cultivars were used, glyphosate resistance resulted in greater yield and net returns. Use of PRE + POST vs. POST-only weed control did not significantly affect yield, but did result in lower net returns when the MG IV GR cultivar was used. As in the previous 2 yr, the lack of a significant fall tillage × WMS interaction indicates that tillage environment had no effect on results.

CONCLUSIONS

Fall ST compared with fall DT was associated with a decline in redvine control in non-GR cultivars but not in GR cultivars. However, this increased redvine presence was not associated with a yield decline. At the conclusion of the study in 2002, johnsongrass control was ≤40% in non-GR cultivars regardless of fall tillage treatment. When GR cultivars were used in either tillage environment, control of johnsongrass was ≥93%. These results indicate that the extra expense incurred from using DT for perennial weed control is not justified when GR cultivars are used in this environment. This is counter to the premise of Koskinen and McWhorter (1986) that continued use of shallow or minimum tillage may result in increasing levels of perennial weed infestations, which was proffered before GR cultivars were in use. The heavy johnsongrass pressure in non-GR cultivars in 2002 was associated with lower yields and net returns from the WMSs with non-GR cultivars.

The greater expense associated with use of PRE + POST compared with POST did not translate into increased yields, but resulted in lower profits in some cases regardless of tillage treatment. This finding supports those of earlier-cited studies. It is noted that the POST non-GR programs in 2001 and 2002 contained residual herbicides (fomesafen in 2001 and metribuzin in 2002; Table 2), and these would have been beneficial for late-season weed control in non-GR soybean. Total POST programs that would have relied on nonresidual herbicides may not have been as successful.

Direct comparisons between tillage treatments are not valid because replicates are subsamples of tillage treatment. However, trends did occur. In 2000 and 2001 when low and untimely rain coincided with MG IV reproductive development, average yields and profits from MG IV cultivars grown in DT were 2357 kg ha^{-1} and \$101 ha^{-1}, whereas those from ST were 1672 kg ha^{-1} and \$20 ha^{-1}. In 2002, when rain patterns were timely for MG IV reproductive development, this trend did not occur. When later-maturing MG V cultivars were used, there were no trends for differences in profits resulting from using different fall tillage treatments. These trends support the findings from earlier-cited reports.

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